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FUTURE DIRECTION PAPER

New Sensing Technologies for Monitoring Machinery, Structures, and Manufacturing Processes

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Abstract: Sensing is the fundamental technique for sensor data acquisition in monitoring the operation condition of the machinery, structures, and manufacturing processes. In this paper, we briefly discuss the general idea and advances of various new sensing technologies, including multiphysics sensing, smart materials and metamaterials sensing, microwave sensing, fiber optic sensors, and terahertz sensing, for measuring vibration, deformation, strain, acoustics, temperature, spectroscopic, etc. Based on the observations from the state of the art, we provide comprehensive discussions on the possible opportunities and challenges of these new sensing technologies so as to steer future development.

Keywords: fiber optic sensor; metamaterials sensing; microwave sensing; multiphysics sensing; terahertz sensing

I. INTRODUCTION

This paper reflects on the important aspects in the field of new sensing technologies for the dynamic monitoring of machinery, structures, and manufacturing processes. Opportunities and challenges as well as future directions are discussed. Section II on multiphysics sensing (MPS) for manufacturing process monitoring was completed by Professor Robert Gao from Case Western Reserve University and Dr. Zhaoyan Fan from Oregon State University. Section III on advances of smart materials and metamaterials for acoustic and vibration sensing was written by Professor Qingbo He and Dr. Tianxi Jiang from Shanghai Jiao Tong University. Section IV on the overview of microwave vibration and deformation measurement and future research opportunities was written by Professor Zhike Peng and Dr. Yuyong Xiong from Shanghai Jiao Tong University. Section V on opportunities and challenges in fiber optic sensors was written by Professor Luc Thévenaz from École Polytechnique Fédérale de Lausanne. Section VI on recent progress of electromagnetic metasurfaces enhanced terahertz sensing was written by Professor Shuncong Zhong and Dr. Yi Huang from Fuzhou University.

II. MPS FOR MANUFACTURING PROCESS MONITORING

A. OVERVIEW

MPS refers to the integration of multiple physical sensors and sensing modalities to comprehensively capture the dynamical behavior of physical systems or processes. Compared to conventional approaches where sensors measure a single type of physical phenomenon for system and/or process monitoring, MPS takes multiple simultaneous measurements on the same target based on different physical principles and is inherently capable of capturing information from different perspectives, for improved measurement accuracy and reliability.

The history of MPS can be traced back to the early 1980's when researchers began to investigate the use of different types of sensors to measure different physical quantities associated with the same object or system [1].

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At the early stage, research on MPS was primarily focused on two objectives: 1) developing new sensing methods for more accurate and reliable measurements for applications that require precision in operation such as robotic systems [2], and 2) integrating multiple sensing modalities to create a more comprehensive representation of a physical system or process by combining data from multiple sensors, such as vision, acoustic, and magnetic sensors [3].

To achieve the first objective, researchers worked on developing sensors that simultaneously measure multiple physical quantities, such as temperature, pressure, and flow rate. This approach led to the development of new sensor technologies such as micro-electromechanical systems (MEMS), which enabled the creation of sensors that could measure multiple physical quantities in a single device. It further led to new data fusion techniques for integrating data from multiple sensors to model the relationship between the measured data and the target of measurement such as product quality and tool life, using neural networks or Bayesian theory. In the last decade, with the development of new integrated sensors and the emergence of the Internet of Things (IoT) and Industry 4.0, the focus of MPS has been expanded to complex, dynamic, and harsh environments using wireless sensors and sensor networks, we will use new data processing and data fusion techniques, such as cloud-based deep learning that can analyze large volumes of data in real time and accordingly generate control decisions.

A general MPS system has four major functions: 1) the ability to detect physical phenomena associated with the target systems or processes, 2) the ability to convert physical phenomena into scaled signals in a digital form, 3) the ability to extract characteristic features from the raw data, and 4) the ability to quantify or infer the target values that can be verified by ground truth measurement. For manufacturing process monitoring, the design of MPS system and the associated working principle, and its performance in terms of accuracy, stability, and robustness are highly dependent on the physical nature of the target systems or processes. In the next sections, research on MPS is discussed for three categories of manufacturing processes: ***metal cutting***, ***injection molding***, *and* ***additive manufacturing***. In Fig. 1, an overview of the key functionalities of MPS system is shown.

B. ADVANCES OF MPS IN MANUFACTURING PROCESSES

1) METAL CUTTING. Metal cutting utilizes a broad range of manufacturing processes such as milling, turning, and grinding, where different types of cutting tools remove a certain volume of materials from the workpiece under certain speeds by following a predetermined trajectory. Table I provides a summary of the major types of MPS methods reported in the literature. During metal cutting, the cutting force is generated at the tool-workpiece interface and affected by the depth of cut, friction between the cutting tool and workpiece (tool wear), and vibrations of the cutting tool [4]. Temporal stability of the cutting force affects the produced surface topology and the lifetime (wearing status) of the cutting tool. For cutting force measurement, force sensors or dynamometers that measure the cutting forces

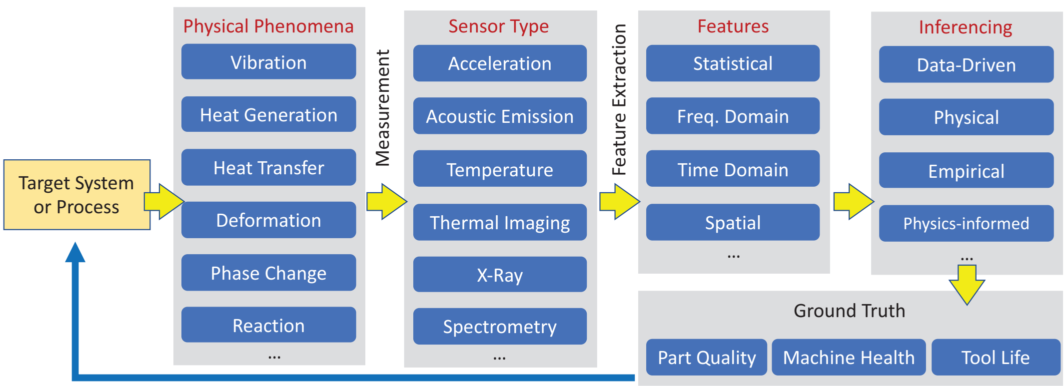

Fig. 1. An overview of multiphysics sensing.

Table I. MPS for cutting process monitoring

	Multi-physics Sensors					
Reference	**Force**	**Vibration**	**Acoustic Emission**	**Temperature**	**Others**	**Target of Monitoring**
[5]	Tool	Tool				Tool wear
[11]			Yes			Tool wear
[6]	Tool	Tool	Yes			Surf. roughness
[8]		Tool	Yes		Motor current	Tool wear
[9]		Spindle	Yes			Chatter
[7]	Tool	Tool		Workpiece		Tool wear
[12]					Spindle speed, tool displacement, pressure	Fault diagnosis
[10]		Spindle				Tool wear

along the cutting and feeding orientations have been the major type of sensors reported in the literature [5–7].

To address the limited bandwidth of force sensors and dynamometers, acceleration sensors were investigated for capturing the dynamics in tool and workpiece vibrations [5,6,8–10]. Acoustic emission sensors can partially fulfill the role of accelerometers in cases where it is difficult to place sensors directly on the cutting tool [5,6,8,9,11]. In such cases, acoustic emission sensors can measure the acoustic (1 Hz to 25 kHz) wave generated during the cutting process from which vibration frequency and variations in the vibration amplitude can be estimated. As the cutting process also generates a large amount of heat, temperature is another sensing modality commonly used for monitoring the metal-cutting processes [7]. In addition, information on machine tool operations, such as motor voltage, motor current, spindle speed, feed rate, and preset cutting depth [8,12], is collected from external or machine-integrated sensors for research on metal cutting processes.

2) INJECTION MOLDING. Polymer injection molding process consists of four major stages [13]: 1) plasticization, where the raw material is melted and injected into a rotating barrel; 2) injection, during which melted polymer is injected into a mold cavity; 3) packing, holding, and cooling, during which additional polymer melt is forced into the cavity under high pressure to compensate for the volumetric shrinkage until the part is sufficiently solidified; 4) ejection, where the mold opens, and the molded part is ejected by push pins.

Of the various parameters that affect the product quality in injection molding, temperature, and pressure distribution within the mold cavity are the two most critical parameters [14]. Another two parameters of the melt material, melt flow velocity and melt viscosity, also affect the part quality in terms of variations in the part length [15]. Simulation of the injection molding process has shown that part quality can be explained by the four melt parameters as described above with an accuracy of up to 92.5%. The accuracy can be further improved to 95.7% if the mold temperature is also included [16].

Table II summarizes MPS techniques developed to monitor injection molding processes. As an example, Wang *et al.* [17] built an online monitoring system using ultrasonic transducers to send a series of pulses to the polymer part through the mold. The ultrasonic waves are reflected at the boundary between two different media (e.g. polymer melt/mold, or air/mold) and the amount of energy of the ultrasonic signal is directly reflective of the material property. This technique has been used to detect the flow front of the polymer melt and the forming of air gaps during the packing/cooling stage. Similarly, Wright and Hutchins [18] used this technique to monitor the burnout of a polymer binder from an injection molded ceramic component. Lynnworth *et al.* [19] introduced a multi-zone waveguide in which the dependence of the ultrasound velocity on the temperature was utilized to measure the mold temperature. Trivedi *et al.* [20] developed ultrasonic thermometers for injection molds based on a similar concept.

Prior efforts have led to the invention of novel, acoustic wireless sensors that measure or infer a total of four parameters related to the polymer melt within the cavity: pressure, temperature, flow front velocity, and melt viscosity. The measured signals are transmitted to an external signal receiver through coded ultrasonic waves. Further efforts were reported for the measurement of melt velocity and viscosity using multiple wireless sensors embedded in the mold cavity [21].

3) ADDITIVE MANUFACTURING. Additive manufacturing (AM), also known as 3D printing, produces components incrementally based on the computer-aided design (CAD) model in a layer-by-layer manner [22]. Two major categories of AM in terms of processing metal powder materials are laser powder bed fusion (L-PBF) and direct energy deposition (DED). In the L-PBF process, one or multiple laser beams move on the build platform according to the CAD model and the scanning strategy to melt the spread metal powders into liquid state. DED processes, including Laser DED (L-DED), Electron Beam DED (EB-DED), and Wire Arc Additive Manufacturing (WAAM), employ high-energy heat sources to melt wire or powder materials ejected from a nozzle close to the heat source to stack up the desired structure. For both L-PBF and DED processes, the status change of metal materials, from their original form of powder or wire through the fluid phase under high temperature, until fully solidified after cooling, determines the quality of the produced parts in terms of the material's density, strength, residual stress, material homogeneity, surface roughness, and generation of defects such as pores, keyholes, and delamination cracks. As a result, the temperature distribution surrounding the melt pool during AM becomes the most commonly measured parameter for online monitoring.

Acoustic emission sensors have also been investigated for monitoring noise generated from the melt pool, which results from the high-energy density applied during the printing process [23]. As another sensing modality, Peng *et al.* [24] designed a system that simultaneously captures visible and infrared light during the L-PBF process to detect defects in the built parts. The same research group [25] expanded their efforts further with an additional CMOS sensor to capture polarized images, which can highlight the edge contour hence detecting the defects, such as cracking,

Table II. MPS for injection molding process monitoring

References	Multi-physics Sensors				Target of Monitoring
	Pressure	Temperature	Velocity and viscosity	Others	
[14]	Mold, hydraulic	Mold, product surface			Part quality
[15]	Post gate Barrel	Post gate		Clamping Force	Part quality
[17,18]			Melt		Part quality
[19,20]		Melt	Melt		Process parameters
[16]	Melt	Melt			Part quality
[21]	Melt	Melt	Melt		Part quality

Table III. MPS for additive manufacturing process monitoring

Reference	Multi-physics Sensors					Target of Monitoring
	IR	Visible Light	Temperature	Acoustic Emission	Others	
[24]	Sample surface	Sample surface				General defects on the surface, LPBF
[25]	Sample surface	Sample surface				Cracks and pores, LPBF
[26]			Melt pool (Photodiode)	Fabrication process		Porosity, LPBF
[27]		Sample surface	Melt pool (Photodiode)	Fabrication process		Porosity, LPBF
[28]	Melt pool and spatters		Build plate (pyrometer)			Spatters and delamination, LPBF
[29]	Melt pool				Geometry (Profilometer)	Process stability, DED
[30]	Melt pool					Porosity, hump, WAAM

more effectively. Li *et al.* [26] collected one-dimensional acoustic and photodiode signals from a L-PBF process. They subsequently converted the collected signals into two-dimensional images based on a sliding window. With the converted images, a convolution neural network (CNN) has been trained to fuse the features from the acoustic and photodiode images to detect the built quality. The authors then expanded their investigation by adding a digital camera to the system to capture the surface of each printed layer during the layer-wise printing process [27]. The CNN model that was trained by these three types of data exhibited the best performance in terms of classification accuracy and quality detection. Yakout *et al.* [28] utilized a high-speed infrared camera and pyrometer together to successfully detect the spatter particles and delamination during the L-PBF process. The infrared camera captured the spatter particles, and the pyrometer detected the temperature of a single point within the fabrication region that provided accurate cooling rate information.

For DED processes monitoring, Chabot *et al.* [29] designed a close-loop control system by applying a laser profilometer to control the geometry accuracy and an infrared camera to control the melt pool stability. In this study, the geometry accuracy is controlled by the laser travel speed, and the melt pool stability is controlled by the idle time between the layers. In another study by Chen *et al.* [30], a monitoring scheme based on the thermal image is developed to control a WAAM system. The monitoring scheme fused melt pool temperature and profile width of the deposition layer into images based on thermal data from the thermal imager. The fused images have been imported into a residual neural network (ResNet) to classify the defects, such as hump, deposition collapse, pore, etc. In Table III, a summary of MPS for AM process monitoring is provided.

C. CHALLENGES AND OPPORTUNITIES

Continued advancement of computing hardware and data science has facilitated the increasing applications of MPS techniques across a wide spectrum of manufacturing processes and systems. Still, challenges remain in terms of ensuring the high quality of the acquired data that are typically of large volume, from different sources, and associated with uncertainty. Furthermore, how to interpret the data for informed decision-making remains a research issue. Associated with these challenges are also new opportunities for advancing the science-based for MPS systems.

1) SENSOR INTEGRATION. Sensor integration is one of the basic challenges associated with the MPS in a manufacturing environment. From the perspective of data interpretation, it is preferred to acquire data from the target objective in-situ to maximize signal-to-noise ratio (SNR). On the other hand, as the sensors themselves also have specific physical properties such as mass, heat capacity, and thermal/electrical conductivity, sensor integration should not alter the characteristics of the monitored object such that the measured data are reliably reflecting on the dynamics of the object. While miniaturization technologies developed in the 1990's such as MEMS have reduced the dimensions and masses of sensors drastically, constraints continue to exist when integrating sensors into a manufacturing environment. *First*, the increased complexity of manufacturing machines and systems makes it difficult to integrate wired sensors. One example is sensing for injection molding process, where cooling lines embedded within the mold for proper cooling rates distribution across the mold location make it infeasible to route wire connections for sensor powering and signal transmission through the mold structure without significantly affecting the mold structure [31]. Such constraints make self-powered and wireless MPS sensors highly desirable [13]. *Second*, high sensitivity and low structural repercussion on the target system is required for high-precision manufacturing. As an example, the microrolling machine developed in [32] enables surface texture to be generated on the surface of thin metal sheets of several hundred micrometers, at the micrometer scale. For online texture dimension monitoring, sensing methods are needed that do not interfere with the texture generation process. *Third*, advancement in AM has significantly pushed the envelope of material processing with temperatures reaching over 1600°C for processing alloy powders or wires [33]. Although noncontact sensors such as IR cameras can capture the temperature of the melt pools, calibration of the sensors due to emissivity changes continues to remain a challenge for accurate temperature measurement.

2) DEPENDENCY ON SENSOR DATA. In monitoring manufacturing processes, multiple features may be extracted from the raw sensor data as characteristic and quantitative representatives of the sensing modalities, as shown in Fig. 1. As the sensor types and features are selected based on the prior knowledge of the target system, there are certain correlations between each of the features and the target being monitored, such as part quality, tool life, and machine health condition. At the same time, the features extracted from the same or different types of sensors could also correlate with each other depending on the sensing principle. As highly correlated data features do not contribute to increasing the information content, directly processing the extracted features results in low efficiency in computation and extra time delay in data analysis, especially for the applications with large amounts of MPS data sampled.

Testing the cross-correlation among data features to determine the utility and contribution of each of the features to the goal of the monitoring tasks can be realized through orthogonality analysis [21] and principal component analysis (PCA). PCA transforms data feature values into principal components in an orthogonal space by assuming that the sensor data and the target of monitoring are linearly correlated. This, however, is not always true in real-world systems. Alternative methods have been investigated, e.g., Kernel-based Partial Least Square (KPLS) [21], which integrates principal components with nonlinear correlation analysis. Different from PCA, KPLS first transforms sensor data to a lifted dimensional space to account for nonlinearity in the data, and then decomposes sensor data into orthogonal components that have the highest correlation with the fusion target. As a result, variation in the fusion target that indicates deviation in the part quality can be distinctively related to the components.

3) INFERENCING TARGET PARAMETERS FROM BIG DATA. While a large number of sensors are used for monitoring a complicated system or process, the large amount of data generated by sensors has brought the concept of big data to MPS systems. As sensors could generate false data due to sensor failure, environment noise, circuitry noise, and miscommunication during data transfer, uncertainties from each error source can aggregate and result in low data quality. For big data processing, deep learning (DL) has been investigated as a tool for extracting the underlying patterns hidden in the data. However, the general “black-box” nature of DL algorithms has hindered its widespread acceptance in the industry. To promote the trustworthiness in DL, data curation and model interpretability methods have received significant attention in recent research. Examples include data denoising, data cleansing, data synthesis, semantic annotation, relevance analysis, attention mechanism, and incorporation of physical principles into DL structure, which represent ongoing and future research topics of high interest to the sensing and manufacturing communities [34].

D. FUTURE RESEARCH DIRECTIONS

Recognizing today’s challenges in MPS, future research efforts in the following directions are expected:

- *Self-powered and power-efficient sensor design*: To integrate sensors within complex structures, sensor self-powering through energy harvesting from the environment or the physical system being monitored is highly desirable. Also, incorporating multiple sensing principles within a single package will facilitate improved accessibility of the sensor to difficulty-to-reach places in machines and/or processes for high-quality data acquisition in close proximity to the source of signal generation.
- *Non-contact sensing*: New sensing methods based on optical and other field-coupling principles will be of high interest to manufacturing where low interference and high measurement accuracy are required.
- *Model-integrated sensing data analytics*: Combining data science with physical models that describe the dynamics of the sensing target will provide a physical basis for interpreting the data measured for improved transparency and trustworthiness of the analysis results.
- *Compressed sensing*: Leveraging data compression to allow large amount of information to be encoded, transmitted, and recovered beyond limitations in sensing physics.

III. ADVANCES OF SMART MATERIALS AND METAMATERIALS FOR ACOUSTIC AND VIBRATION SENSING

A. OVERVIEW

Sound and vibration carry a wealth of useful physical information in the real world, which is crucial for discovering knowledge in various fields. Acoustic sensing is one of the most natural noncontact sensing approaches, which has broad applications in voice interaction, communication, medical imaging, and dynamic monitoring and diagnosis. In practical environments, sometimes it is hard to extract the inner physical information of structures by simply measuring the external acoustic signals. Developing vibration and elastic wave sensing technologies can not only fundamentally solve the noise problems of mechanical systems but also play important roles in health care, the Internet of Things, and smart cities [35,36]. Current acoustic and vibration sensing technologies with commercial sensors suffer from low sensitivity and resolution, weak SNR, impedance mismatch, rigid construction, complex hardware, bulky device size, and high cost. These problems motivate efforts to design various new sensing devices. In this review, we introduce the state-of-the-art of new material sensing with smart materials and metamaterials and discuss the future directions of sensing technologies for dynamic monitoring and diagnosis.

B. ADVANCES OF NEW MATERIAL SENSING TECHNOLOGIES

1) SENSING WITH SMART MATERIALS. One of the sensing principles with smart materials is to efficiently convert mechanical signals into electronic signals, which mainly includes two conversion mechanisms, namely piezoelectric and triboelectric effects [37]. The piezoelectric effect that has been applied in mechanical sensors is the direct piezoelectric effect. The deformation of certain dielectrics under an external force induces charge accumulation, creating a voltage cross the dielectric. Due to the instantaneous formation of a piezoelectric potential upon deformation, these sensors exhibit a fast response time and an excellent high-frequency response for vibration measurements. For triboelectric sensors, triboelectric charges are produced due to the coupling effect of contact electrification and electrostatic induction when two different materials come into friction contact. Triboelectric nanogenerators have been widely investigated for self-powered flexible mechanical sensors. The output signals are influenced by both the magnitude and frequency of the external mechanical stimuli, so they are mostly suitable for dynamic force sensing. Another sensing principle is to measure the changes in electrical properties under the mechanical stimuli, such as piezoresistive effect and piezocapacitive effect. Different from the self-powered sensors based on piezoelectric and triboelectric effects, these designed mechanical sensors require externally supplied power sources. In addition to the sensitive properties of materials, improving the coupling at the interface between different media is also important for improving the sensing efficiency. Smart materials such as hydrogels and liquid metals for impedance matching have been widely used in hydroacoustic detection and ultrasonic imaging [38,39].

The following will introduce some representative works of sensing with smart materials in various application fields. In human–machine interaction, flexibly piezoelectric membranes can be used for highly sensitive voice sensing in a broad frequency band [40]. The multi-resonant voice spectrum is achieved by adopting the lead-zirconate-titanate (PZT) thin film on an ultrathin polymer membrane for the mobile-sized acoustic sensor. In structural health monitoring and mechanical fault diagnosis, a triboelectric rolling ball bearing with self-powering and self-sensing capabilities is proposed [41]. The abnormal states caused by mechanical failures can be monitored in real time by measuring the decrease in output current to avoid major accidents. Multifunctional sensing is a trend in structural health monitoring. A bio-inspired, intelligent flexible sensing skin is demonstrated for multifunctional flying perception [42]. The sensing system is composed of piezoelectric sensors, hot-film sensors, capacitive pressure sensors, and temperature and strain sensors to obtain the flutter, impact locating, wind pressure, temperature, and strain of aircrafts. The skin-like mechanosensing, neuron-like data transmission, immune system-like impact monitoring, and brain-like artificial intelligence of the sensing skin show great application potential for unmanned air vehicles and underwater vehicles. In medical imaging, a wearable ultrasound imaging device is proposed that consists of a rigid piezoelectric probe array robustly bonded to the skin with an acoustically transparent hydrogel-elastomer hybrid [43]. The device can be comfortably worn for 48 hours and hooking up to a commercially ultrasound platform for continuous long-term ultrasound imaging. Recently, the ultrasound imaging device that features liquid metal composite electrodes are designed to improve the mechanical coupling between the device and human skin, allowing the left ventricle to be examined from different views during motion [44].

2) ACOUSTIC SENSING WITH METASTRUCTURES. The classical diffraction limit and spatial sampling theorem are the two physical laws that dominate conventional acoustic sensing performance. Metastructures can break through the classical diffraction limit by using mechanisms such as negative refraction, anisotropy, and resonant tunneling to achieve subwavelength focusing and super-resolution imaging [45]. The directional selective responses and spatial coding properties of metastructures can overcome the limitation of spatial sampling theorem for sound source localization with high precision and compact dimension [46]. Besides, sensitivity and SNR are two important factors in acoustic sensing. Metastructures can enhance weak acoustic signals through energy localization. According to the application scenarios, acoustic sensing with metastructures can be roughly classified into the following categories: directional sound source detection and multiple source identification.

In terms of directional sound source detection, anisotropic metamaterials with graded high-refractive index have strong wave compression effect and pressure amplification, thereby enabling outstanding SNR and remarkable directional responses, which can be used for enhancement of weak mechanical fault signals [47,48]. Line-defect phononic crystal has also been demonstrated to have desired acoustic energy enhancement and directional localization with Fabry-Perot-like cavity resonance [49]. This model further inspires the design of the compact grating structures with large refractive index. Moreover, needle-like directional sensing and demultiplexing are achieved based on topological valley transport [50,51]. By taking advantage of the resonance, metastructures can achieve acoustic sensing at low frequency (<1000 Hz). Space-coiling structure is one typical structure that is capable of manipulating acoustic waves at low frequency. Mie resonances induced by space-coiling structures can be used for direction finding and nonradiative transceiving of ultra-weak sound [52,53]. For passively sensing sound source with unknown distance and amplitude, Fano-like resonance realized by coupled Helmholtz resonators is proposed [54]. The device can detect the angle of an incident wave in a full angle range. Recently, locally resonant phononic crystal plates with point defects are demonstrated to achieve superior wave confinement and outstanding SNR at low frequency, which shows promising application prospects in voice-based human–machine interaction, machine condition monitoring, factory exploring, and rescuing systems under strong background noises [55]. Overall, the above studies based on metastructures surpass traditional methods in directional sensing and enhanced sensing of acoustic waves.

In terms of multiple sound source identification, a framework that combines spatial coding metastructures with computational reconstruction algorithms is proposed, which can dramatically reduce the number of sensors to one. The first prototype of metamaterial-based single-sensor multi-speaker listener comprises randomized Helmholtz resonator array [56]. The metamaterial can provide diverse frequency-dependent modulation and spatially complex measurement modes, usually referred to as spatial coding. The spatial transmission of metamaterial is highly uncorrelated because of spatial coding, which can be considered as an implementation of the sensing matrix at the physical layer. Combining with the reconstruction algorithm of compressive sensing, the metamaterial device can achieve sound source localization and separation with only one microphone. With this framework, a concept of single-sensor acoustic camera is demonstrated for planar acoustic imaging by using metamaterial with anisotropic random effective refractive indices [57]. The dimension of multiple source localization has also been extended to 3D space [58]. These efforts provide attractive opportunities beyond traditional techniques in intelligent scene monitoring, robotic audition, and nondestructive evaluation. Similar to compressive sensing approach, spatial coding metalens is proposed to translate the evanescent waves into the propagating waves. High-quality images of far-field subwavelength objects can be reconstructed by using computational ghost imaging algorithms [59]. In addition to metamaterials, randomized acoustic coding apertures are designed for 3D ultrasound imaging and photoacoustic imaging with a single transducer/detector [60,61], showing promising application prospects in medical imaging and clinical diagnosis with cheaper, faster, simpler, and smaller sensing devices.

3) VIBRATION AND ELASTIC WAVE SENSING WITH METASTRUCTURES. In practical applications, acoustic signals can be easily overwhelmed by other mechanical noises. The conditions of human body and mechanical systems can be directly obtained by performing vibration and elastic wave detection, where the sensitivity is an important factor to evaluate the sensing performance. For identifying multiple vibration sources, the most common approach is to solve the dynamical inverse problems. Current vibration identification methods typically require information fusion from a large number of sensors because of the similar transfer characteristics in uniform media and the severe aliasing of inner excitations. The sensing performance is greatly affected by the layout of sensors. If the vibration transfer characteristics can be properly designed, it is possible to realize the compressive identification of vibration excitations. Metastructures can also exert their unique advantages in vibration and elastic wave sensing by enhancing signal amplitude and coding spatial transmission.

In terms of vibration and elastic wave detection, current studies based on metamaterials are mainly focused on amplifying useful physical information and suppressing harmful information. For instance, the auxetic metamaterial with negative Poisson's ratio embedded with stretchable strain sensors is demonstrated to be capable of significantly improving the sensitivity for recognizing rich medical details from human pulses [62]. The wavelength of elastic waves can be compressed by programing the bending stiffness of the metamaterial with adaptive piezoelectric circuit systems. Over two orders of magnitude amplification is achieved to overcome the detection limit of flexural waves [63]. The filtering and focusing properties of phononic crystals can be used to naturally select and reflect the higher harmonics generated by nonlinear effects, enabling the realization for nonlinear elastic source detection and damage localization [64,65]. The elastic wave information can also be recognized by driving structural deformations under external stimuli and further recognizing the structural state changes. The stimuli-responsive programmable metamaterial is proposed to be an implementation of mechanical write/read operation for information interaction [66]. The above studies open up avenues for developing novel metamaterial-based elastic wave sensing systems, showing promising application prospects in sensing and evaluation of engineering structures.

In terms of vibration source identification, metastructures can be designed to encode spatial transmission for computational sensing. The randomized resonant metamaterial with randomly coupled local resonators is demonstrated to be capable of producing highly uncorrelated transmissions for different spatial vibrations due to the disordered coupling of random effective masses [67]. The metamaterial can be considered as a physical implementation of sensing matrix. Based on the framework of compressive sensing, multiple vibration sources and impulsive loads can be identified from the measurements of a single sensor. This metamaterial-based sensing system is expected to be applied in wearable devices, quadrotor drones, and aircraft wings. With this design strategy, a local resonant metasurface is further proposed for on-shaft vibration source identification, showing potential application prospects in rotating machinery condition monitoring and fault diagnosis [68]. Moreover, the spatial vibration modulation method is introduced to assist in high-accuracy blade damage localization under single sensor strategies for an industrial quadrotor UAV by arranging silicone-made ring-shaped vibrators with randomly selected structural parameters on the beams of the UAV [69]. For active elastic imaging, a concept of scattering-coded architectured boundary is proposed for computational sensing of Lamb waves [70]. Highly uncorrelated spatial coding is achieved by multiple scattering, ensuring that the object locations can be uniquely identified with only a single transducer. A type of ultrasound touchscreen is designed for interactive input with fewer electronic components. The proposed sensing system can be used for structural health monitoring and flexibly integrated with various smart devices such as household appliances, terminal machines, and industrial equipment as interaction interface.

C. FUTURE RESEARCH DIRECTIONS

We have reviewed the state-of-the-art of the representative advances in sensing with new materials, especially metamaterials. The studies provide inspiration and promising perspectives for designing novel sound and vibration sensing strategies with simpler, cheaper, and smaller devices. In this section, we discuss the future directions and research prospects from three aspects: the combination of smart materials and metamaterials, computational sensing with metamaterials, and artificial intelligence with metamaterials. We believe that with the development of these aspects, it will bring revolutionary changes to sound and vibration sensing technology for dynamic monitoring and diagnosis and promote multidisciplinary integration and innovation.

1) THE COMBINATION OF SMART MATERIALS AND METAMATERIALS. Currently, the smart materials and metamaterials have been combined for tuning the parameters of metamaterials in the design of adaptive bandgap and programmable function [65,71]. In the future, the combination of smart materials and metamaterials can provide superior performance by expanding the functionality and scope of mechanosensing systems. For instance, piezoelectric coefficients of conventional materials are constrained by the intrinsic crystal structure of the constituent material. By additively manufacturing piezoelectric nanocomposites with complex 3D-printed architectures, piezoelectric metamaterials with arbitrary piezoelectric coefficient tensors can be achieved, which is inaccessible for traditional material design methods [72]. This material-structure-function integrated design paradigm can be applied to create the next generation of intelligent structures. The combination of smart materials and metamaterials can also create new possibilities for mechanical sensing with self-adaptive deformability, ultra-high sensitivity, and programmable functions. Recently, a concept of flexible metamaterial electronics is proposed to include this groundbreaking interdisciplinary field [73]. Self-adaptive conformal electronics and strain sensors can be achieved by using kirigami and origami metamaterials to perform dynamic monitoring on curved surfaces. The shapes and functions of smart metamaterial sensors can be reprogrammed according to environmental conditions or user demands through external stimuli such light, temperature, and magnetic fields. Smart metamaterials can also achieve multi-functionalities by integrating different types of smart materials into a single metamaterial structure. The future direction of sensing with the combination of smart materials and metamaterials is promising but also challenging. Some of the challenges include designing optimal structures for specific applications, fabricating complex geometries at micro- or nanoscale, characterizing dynamic responses under multiple stimuli, and ensuring reliability and stability over time.

2) COMPUTATIONAL SENSING WITH METAMATERIALS. The future directions for computational sensing with metamaterials mainly include three aspects. (1) Modeling of spatial coding. The performance of computational sensing with metastructures is determined by the spatial coding. Currently, experimental calibration is the most effective method to obtain a prior knowledge of the spatial coding of metastructures due to the unavoidable gap between the actual sample and the theoretical model. However, this process is very time-consuming, and only a few discrete spatial positions can be calibrated. If a theoretical model can be established to accurately predict the spatial coding properties of metastructures and build a mapping between the spatial positions and transmission, the burden of the calibration process can be reduced, and the problem that the source information cannot be reconstructed due to the lack of calibration can be overcome. Dynamical modeling with machine learning and artificial intelligence is one way to address this issue. The spatial coding of metastructures can be learned from simulation and experimental data. (2) Computational algorithms. In current studies, the source identification is partly dependent on some pre-knowledge of signals, which is also a reason for pre-experimental calibrations. It is hard to identify the source locations of the unfamiliar continuous signals. Combining the theoretical model with machine learning algorithms may be a possible approach to address this issue. Reconstructing the temporal waveforms of multiple source signals is also a challenging but essential research direction. Innovative coding mechanisms, design strategies, and advanced signal-processing algorithms need to be further explored. (3) Structure design. Current studies generally use empirical redundant design strategies to achieve a desirable transmission coding, which leads to bulky device sizes. By optimizing the metastructures, the useless microstructures can be reduced while maintaining the sensing performance. Meanwhile, the conformal integration of metastructures and mechanical systems is also a crucial direction that needs to be developed, so the metastructures can be applied in various practical scenarios.

3) ARTIFICIAL INTELLIGENCE WITH METAMATERIALS. An interesting future direction of dynamic sensing is the combination of artificial intelligence with metamaterials. The relevant studies can be divided into two categories. One is to encode physical fields with metamaterials to enhance or modulate the characteristics of physical information, and then use artificial intelligence algorithms to process the encoded signals. For instance, it is impossible to image sound sources with spatial features much smaller than the wavelength by directly using a neural network to process the far-field measurement data because information about subwavelength features is evanescent and cannot reach the far field. However, by using a metamaterial placed in the near field, the information contained in the evanescent waves can be encoded into the information carried by propagating waves. The subwavelength pattern can thus be imaged by employing deep learning algorithms [74]. As data volumes grow, conventional silicon-based neural network computing architectures face problems in energy consumption and processing speed due to the analog-to-digital conversion and the signal transmission between memory and logic devices. High efficiencies computing architectures such as analog computing and neuromorphic computing have emerged. The second category of the future direction is designing physical neural networks with metamaterials to perform machine learning in real time and without power consumption [75]. This sensing paradigm is achieved by establishing a mapping between the wave propagation process and the digital artificial neural network model. More generally, a backpropagation method is demonstrated to be capable of training an arbitrary mechanical system as a deep neural network [76]. These perspectives pave the way for design novel machine-learning platforms and show promising potential in dynamical monitoring and diagnosis, but developing a usable device for practical applications still has a long way to go.

IV. OVERVIEW OF MICROWAVE VIBRATION AND DEFORMATION MEASUREMENT AND FUTURE RESEARCH OPPORTUNITIES

A. A BRIEF INTRODUCTION

Vibration and deformation phenomena are universal from the natural world to engineering, such as heart beat, vocalize, and bridge vibration. In the context of engineering, the vibration sensing, analysis, and control are essential for the service of equipment and structures, and the vibration and deformation measurements are the first prerequisite and basis. In particular, the vibration and deformation sensing plays a significant role in equipment fault diagnosis, predictive maintenance, and structural health monitoring (SHM). To this end, several vibration measurement techniques and instruments have already been developed, such as accelerometers, eddy current sensors, digital image correlation with image streams, and laser Doppler vibrometers, which have been widely used in numerous applications. However, the current vibration measurement techniques have some fundamental drawbacks such as high-accuracy, large detection range, and harsh environment adaptability. Therefore, it is highly desired to develop novel vibration measurement approaches to overcome the limitations of traditional techniques.

Fortunately, the emerging microwave vibration measurement technology [77] shows appealing advantages and potentials to address the challenges mentioned previously. The corresponding measurement theory, method, and instruments are investigated to promote the development of this innovative vibration measurement technology in recent years. According to the working modes, the microwave vibration measurement can be divided into two main solutions, i.e., CW Doppler (single-frequency continuous wave) and linear frequency-modulated continuous wave (LFMCW) radar-based approaches [78]. The CW Doppler radar-based approach is commonly used for vibration and deformation measurement of a single target or point, which is performed by nonlinear phase demodulation of baseband signals. Thus, several typical methods are proposed to extract the time-domain displacement signals or vibration frequency such as complex signal demodulation [79], arctangent demodulation [80], and parameterized demodulation [81]. In addition, the radar sensor with advanced six-port architecture is developed to be capable of high measurement data update rates with reasonable system costs [82]. To achieve the capacity of simultaneously and accurately measuring vibration displacements of multiple targets or points, the LFMCW radar-based approach is developed, whose basic principle is interferometric phase evolution tracking across sweep times [83]. Obviously, the displacement measurement rate of this approach is limited by the sweep period, suffering problems in the scenario of high-frequency vibration measurement. To solve this issue, a novel signal processing chain in fast time allows sensing of significantly higher vibration frequencies than the sweep rate [84]. In addition, to improve the measurement accuracy and robustness in real-life scenarios, the static clutter elimination [85], measurement accuracy self-evaluation [86], and multi-scale displacement measurement [87] methods are investigated, respectively. It should be noted that, to get rid of the tricky coupling clutter interference generating from the adjacent targets and surroundings, the LFMCW radar-based method is commonly employed for accurately measuring the vibration displacements of multiple targets which located far enough apart (i.e., much larger than the range bin). To this end, the active transponders [88] and passive harmonic tags [89] are proposed for eliminating the coupling clutter in practical applications.

Furthermore, to achieve a wide range of applications in engineering, the microwave full-field vibration and deformation measurement is highly desired, enabling long-distance, large-scale, and accurate displacement measurement of a large number of measuring points in full field of view. Traditionally, the synthetic aperture radar (SAR) interferometric method is investigated to measure displacement variation over long-distance, enabling round-the-clock monitoring of large-scale subsidence and landslide warning [90]. However, since the SAR imaging is commonly achieved by the orbital movement, it is difficult to sense most of vibration phenomena. To map and quantify tiny motions spanning macroscopic to μm length scales of full-field targets simultaneously and accurately, the millimeter-wave full-field micromotion sensing (MFMS) method is proposed, which measures the displacements via the interferometric phase evolution tracking from the range-angle joint dimension integrating with full-field localization and tricky clutter elimination [91]. For real-life scenarios, the MFMS method can be practically implemented by microwave sensing device equipped with multiple-input multiple-output (MIMO) antenna array to achieve high angular resolution with a relatively small real aperture. In addition, the scanning microwave vibrometer is developed for full-field and remote vibration sensing, which is realized by fast phase-encoded synthesis beam scanning and the corresponding displacement measurement method is established under this sensing mechanism [78].

In terms of application researches, the emerging and developing microwave vibration technology has great potential for using in various fields. Particularly, the microwave radar-based vital signs detection is deeply investigated by different researchers around the world [92–94]. The basic idea underlying this application is sensing the tiny chest wall movement caused by cardiopulmonary activity and further processing of the measured displacement signals, enabling ultimately achieve the expected respiration and heartbeat rates, even the heart rate variability. The technique can be conducted with long-term monitoring regardless of the private problems and light conditions, which is appealing and useful for healthcare monitoring, sleep quality evaluation, and emotion recognition. Currently, the difficulty preventing the widespread use of this technique in daily life is mainly the random body movement interference and robustness in complex scenarios, which can be solved by the advancement of both hardware and signal processing aspects. In civil engineering, the microwave vibration sensing-based SHM of bridges and buildings has attracted much interest [95,96], such as bridge static and dynamic deflection measurement, model analysis, and cable force monitoring. In addition, to improve the accuracy and reliability, a structural displacement estimation technique is proposed that fuses measurements from a collocated accelerometer and LFMCW radar at displacement estimation location on a structure [97]. Therefore, regarding the microwave vibration measurement-based SHM of bridges and large buildings, it shows appealing advantages in contactless multi-point simultaneous measurement, long-detection range, high displacement accuracy, and 24/7 monitoring capability, offering an effective way for remote vibration and deformation monitoring of large structures. Furthermore, considering the sound is essentially produced by tiny vibrations with relatively high frequency, the RF (radio frequency) microphone is proposed to provide an innovative approach for multiple sound source localization and sound signal reconstruction [15], which has high adaptability in the strong noise and complex acoustic environment. In addition, several advancements have been achieved recently in this topic, such as high-quality sound signal recovery and vocal signal detection [98–101].

B. OPPORTUNITIES AND CHALLENGES

Surely, the microwave vibration measurement technology has shown appealing advantages and it deserves with continue development in the future. Here, we summarize some opportunities and challenges for this emerging technology as follows.

1) MEASUREMENT THEORY AND METHOD. As illustrated previously, full-field vibration measurement with high accuracy and synchronization is highly desired in various fields. However, although the basic theory and principle of microwave full-field vibration measurement have been established, it is limited by the relatively low angular resolution in microwave sensing, which is determined by the aperture of antenna array. Thus, it is expected to develop super-resolution sensing solutions from both hardware and signal processing aspects and establish the corresponding full-field vibration displacement measurement method. In addition, the current microwave vibration measurement technology can only quantify and measure the displacement along the line-of-sight. Thus, it is looking forward to the microwave three-dimensional (3D) vibration measurement, especially full-filed 3D vibration measurement approaches. With preliminary exploration, the corresponding coordinate system and 3D displacement reconstruction method are established by using three microwave radars, allowing to achieve the 3D space trajectory and displacement of a vibrating target [102]. The complex and significant full-field 3D vibration measurement is left for future investigations.

Moreover, the fusion of different vibration measurement technology is another important trend to achieve high-performance and high-robustness for complex scenarios and sensing challenges, depending on respective technical advantages. Particularly, it will be interesting to integrate the visual perception technology into the emerging microwave vibration measurement approaches, which can offer ultra-high spatial resolution and improve the level of visualization.

2) APPLICATION INVESTIGATION AND DEVELOPMENT. Vibration phenomenon is widespread in the natural world of engineering. Therefore, it is desired to exploit more applications in various fields with the novel microwave vibration measurement technology, which can harness the advantages of high accuracy, long distance and wide range, multiscale, and harsh environment adaptability. In this process, the microwave vibration measurement method may need to be updated and improved in specific applications. In addition, the corresponding post-processing methods are expected to become the key points for practical applications. For example, in the context of microwave radar-based vital sign monitoring, the chest wall displacement can be achieved by the microwave vibration sensing system and it is crucial to accurately and robustly estimate the corresponding respiration and heart rates even heart rate variability. Currently, to promote the wide application of these techniques in health care, the issues of random body movement and respiration harmonic interference need to be further addressed. In addition, this contactless vital sign detection approach provides a potential sensing way to be further used for investigating the emotion recognition, sleep monitoring, and heart disease warning. In the applications of structural health monitoring of large bridges and buildings, long-term vibration and deformation monitoring is desired, and the corresponding methods of feature extraction and damage assessment are also valuable to be deeply investigated. With these efforts, the microwave vibration measurement technology will become an important mechanical measurement solution for smart cities and infrastructure.

Moreover, the emerging microwave microphone technology deserves to be exploited in long-distance sound source detection, smart sound source identification, and high-quality sound signal reconstruction, which may provide a revolutionary approach for complex and remote sound sensing.

3) SENSORS AND INSTRUMENTS. To promote wide applications in engineering, the corresponding microwave vibration measurement sensors and instruments with high performance are desirable, which should be towards miniaturization, low power consumption, and high performance. Therefore, in this topic, advancements in hardware architectures are critical to achieving high-performance microwave front-ends and real-time processing capacities. In addition, the monolithic microwave integrated circuit (MMIC) technology is rapidly developed in recent years, which provides a chance for miniaturization of microwave vibration sensing system. For high-frequency vibration measurement, there are large mount of data with a short time and the high-speed digital signal processing (DSP) is required. Fortunately, the field-programmable gate arrays (FPGA) devices can be employed to complete the task with high freedom. At last, the high reliability of the microwave vibration measurement sensors and instruments in real-life applications is crucial for widespread use in engineering, which requires continuous iteration and optimization. As a result, with the advancement of technology and in-depth applications in various fields, different types of microwave vibrometer sensors and instruments with high performance will emerge as times require. We envision that the novel microwave vibration and deformation measurement technology and systems could offer a promising approach for contactless displacement sensing with high-performance and appealing advantages.

V. Opportunities and Challenges in Fiber Optic Sensors

A. A BRIEF INTRODUCTION ON FIBER OPTIC SENSORS

Optical fiber sensors turn out to be a recent key technological progress for monitoring critical infrasctructures, mostly in adverse and harsh environment. This is a consequence of their exceptional properties resulting from the unique nature of their constitutive material: silica glass [103]. They are listed here below for the most relevant ones:

- The optical fiber is electrically insulating and extremely immune to electromagnetic perturbations.
- It is chemically inert and, once incorporated into a structure, does not react with the hosting material and therefore gives excellent resistance to aging.
- It is of small size (0.125 mm or the typical size of a human hair) and can be therefore be seamlessly embedded in a structure, with a negligible volume and mass.
- Many sensing points can be multiplexed along the same fiber, only requiring one or two connections to the processing instrumentation.

It has to be mentioned that the optical fiber itself is extremely cheap and long lengths covering many tens of kilometres can be used for remote sensing. This advantage has in real cases to be somehow counterbalanced by the cost of the processing instrumentation, which is substantially higher than for classical sensors. This restricts the field of applications to critical high-valued assets or to cases where simple classical sensors fail to deliver a proper response.

The most common optical fiber sensors are those based on the so-called *fiber Bragg gratings* (FBG) [104], which is a periodic densification of the material that can be simply realized by irradiating the optical fiber with UV light or femtosecond infra-red light pulses. The spatial periodicity is tuned to be equivalent to half of the wavelength of the light (typ. 1550 nm), so that only light in resonance with the periodic structure is strongly reflected, like a pass-band filter. Using the proper interrogating instrumentation, this resonance wavelength can be quickly and accurately determined, and any change in the FBG spatial periodicity can be tracked.

This period turns out to be modified by a change in the refractive index of the glass material, itself dependent on temperature and any action impacting the density of the material. This makes FBG very sensitive to temperature (easily reaching a milliKelvin sensitivity), but also to any strain applied to the optical fiber: this makes them an excellent substitute for classical strain gauge and deformation can be measured at very high accuracy (typically 10^{-8} relative elongation or 10 microns over 1 km!). Many FBGs can be imprinted along one optical fiber, each showing a distinct resonant wavelength, so that a single sensing line can simultaneously monitor many tens of sensing points through a single connection.

A constitutive penalty of this technology is its irreducible cross-sensitivity to temperature and strain. Despite extensive research to discriminate the effect of these two quantities, no simple solution has been devised to fix this issue with a tolerable loss of accuracy. It must be mentioned that this issue is shared by most of the optical fiber sensors and is not specific to FBGs. Regarding the relatively low cost of the sensing element, the problem is actually mitigated by a simple workaround: it is quite easily to isolate a section of fiber from any mechanical perturbation by a proper packaging (e.g. by loosely inserting the fiber in a tube), while it is unrealistic to isolate it from thermal variations. Hence, one FBG will be sensitive to both temperature and strain, while another one placed in close vicinity will be temperature-sensitive only once packaged in a loose tube. Independent values for temperature and strain can therefore be easily extracted in a statistically well-conditioned procedure.

FBGs are today routinely used in many infrastructures as strain gauges or thermal probes, like wind turbine blades, plane wings, and medical catheters.

Possibly the most attractive potential of optical fiber sensing is the very attractive possibility to realize distributed measurements, by exploiting the optical fiber as a linear sensor continuously delivering a value of the measured quantity at each point along the fiber [105]. This unique property offers key advantages since a direct map of the distribution of a quantity can be obtained using a single fiber, replacing many thousands of point sensors and therefore extending the sensing capability from a point to a fully linear distribution. On a broader point of view, this has widely expanded the general sensing functionality and has simply made the general survey of critical installations technically possible with an affordable investment.

In distributed fiber sensors, the local information is primarily retrieved using time- or frequency-coded signals, which are continuously reflected or back-coupled, primarily using natural scattering processes. In its most widespread implementation called *optical time-domain reflectometry* the optical fiber is probed using a short pulse of light, which is continuously scattered in all directions during its propagation, and a tiny part of this isotropic scattering is recaptured by the fiber to propagate into the backward direction. By a time-resolved analysis of the optical signature of this scattered light, it is possible to retrieve a value of the measured quantity at all positions by converting the time of flight of the signal into a position, just like in a LIDAR or RADAR system. It is clear that these distributed sensing systems are much more sophisticated than point sensors and are dedicated to critical assets.

All the three natural scattering processes observed in silica are exploited for distributed fiber sensing and their specificities are detailed hereafter:

- **Raman scattering**: even though this effect shows the smaller scattering cross-section of all processes, this is possibly the simplest and the most affordable distributed fiber sensor, originally proposed in the 1980's [106]. In the Raman effect, the light is scattered by the internal vibrations of molecules and experiences an important frequency shift of ~13 THz (equivalent to ~100 nm in wavelength unit in the near infra-red) as a result of these very fast vibrations. The light frequency can be downshifted (Stokes scattering) or upshifted (anti-Stokes scattering), and their spectral signatures are clearly and easily separated regarding the large frequency shift. The amount of scattered light for each flavor (Stokes or anti-Stokes) depends on the vibration amplitude that is determined by the background thermal activation, itself a quantum process governed by the Bose-Einstein statistics.

Considering its relatively large vibration energy, a molecule is 8 times more likely to be at rest than excited around room temperature, and this probability is strongly temperature-dependent. It turns out that the Stokes scattering can occur even with a molecule at rest, while the anti-Stokes process requires a molecule to be placed in an excited state. As a function of time, by directly comparing the intensity of the Stokes and anti-Stokes scattered lines from an intense probing light pulse, a value of the temperature can be retrieved as a function of the position, without cross-sensitivity with strain.

This type of sensor is technically easy to implement and is therefore affordable and very successful. The main drawback is related to the very low Raman cross-section giving very weak signals that must be substantially averaged, restricting the response time and the accuracy. Typically, a 1 K accuracy can be obtained every meter over 10 km, after several minutes of time averaging. The other penalty is related to the fact that the information is coded in intensity and is therefore subject to biasing in the presence of wavelength-dependent losses.

- **Brillouin scattering**: this effect is caused by collective lattice vibrations of a solid and also gives rise to spectrally down- and up-shifted scattering lines, though with a much lower frequency shift, of some 11 GHz in the near infra-red. Since it is caused by spatially long-spanning vibrations, according to the uncertainty principle the scattered light is spectrally very narrow (~30 MHz) and the frequency shift can be therefore very precisely determined. It turns out to be proportional to the acoustic velocity in the medium. Hence, it is a powerful technique to determine by a purely optical technique the acoustic properties of a medium, since the acoustic velocity can be readily determined from the central frequency shift of the Brillouin spectral lines, while the width of the scattered spectrum turns out to be directly proportional to the acoustic loss in the medium.

This way, any change of the sound speed in the medium can be precisely and locally detected by retrieving the peak frequency shift of the Brillouin scattered light. The acoustic velocity is temperature- and material density-dependent, so that it makes this technique sensitive to temperature and strain, but indistinctively, with the key advantage of an information encoded in frequency and therefore robust to any bias caused by loss. Moreover, the scattering cross-section is 2 orders of magnitude larger than Raman scattering, thus delivering larger relevant signals and enhanced performance.

Brillouin scattering offers the further advantage of being stimulated under certain conditions, using pump and probe signals launched at each end of the sensing fiber. This strongly enhances the interaction by stimulating the acoustic vibration through the interference of the counter-propagating optical waves, which in turn creates a strong coupling between the optical waves when showing the exact frequency difference ruled by the acoustic velocity. The stimulated flavor of this scattering offers the further possibility to implement sophisticated coding schemes to realize extreme performance, such as centimetric spatial resolutions or very long-distance ranges [107].

Despite the identical signature given by temperature and strain, Brillouin-based sensors are the preferred solution when long-distance range are required with a large number of resolved points. A 1 m spatial resolution can be achieved over ~50 km with a 1 K temperature resolution or a 20×10^{-6} relative detectable elongation (20 microns over 1 m). This remains roughly 3 orders of magnitude less sensitive than point sensing using FBGs, but more than enough for most applications with the further advantage of fully distributed measurement using a fiber without post-manufacturing processing like FBGs. There are trade-offs between spatial resolution, distance range, and accuracy on the measured quantity, but field measurements up to 100’000 resolved spatial points can be achieved, while more than 1’000’000 spatially resolved measurements were achieved in a lab environment [108].

- **Rayleigh scattering**: while this scattering is the easiest to observe, showing a cross-section typically 2 orders of magnitude larger than Brillouin scattering, its sensing signature is the most complex. It is caused by permanent random density fluctuations of the medium that are frozen during glass solidification. These can be imaged by randomly positioned static scattering centers that isotropically deviate a tiny fraction of the incoming light, which is then partially recaptured in the backwards direction with no spectral shift. This elastic scattering process is observed in all disordered media (gases, liquids, and amorphous solids) and is responsible, among others, of the blue color of the sky.

This scattering process has been used for a long time, since the late 1970’s, to diagnose the loss distribution along optical fibers when probed using an incoherent light pulse and is now a routine technique known as *optical time-domain reflectometry* (OTDR).

Much more recently, it was observed that sensitive information could be extracted when probing the medium using a fully coherent pulse. In that case, the back-coupled light from the distinct scattering centers randomly interferes, creating a backscattering time trace showing random intensity fluctuations as the probe pulse propagates along the fiber, visualized like a jagged pattern. This trace turns out to be static and perfectly reproducible if experimental conditions are unchanged (laser wavelength and fiber environment).

If the optical path length between scattering centers is modified, the phase of the interfering waves from the distinct scattering centers is also changed and the interference pattern is significantly altered. An optical path change can be created by a minute fiber deformation, such as caused by an acoustic vibration, turning the optical fiber into a sensitive distributed microphone. This is today the major application of coherent distributed Rayleigh sensing and is commonly designated like *distributed acoustic sensor* (DAS). It covers a vast domain of appealing applications such as intrusion detection, seismic event monitoring and localization (sometimes simply reemploying submarine telecommunication cables) and a vast variety of other events characterized by a typical acoustic signature.

With a bit of misfortune and as a short-sighted consequence of these successful applications, all coherent Rayleigh distributed sensors are too often erroneously designated as “DAS” and this puts a shade on the much broader field of applications that this type of sensing can address. It turns out that coherent Rayleigh sensing can also achieve distributed temperature or strain sensing, just like Brillouin sensors, but with a much better accuracy, though at the expense of a more sophisticated implementation than DAS.

Before detailing the principle, it must be first clarified that the response is actually built from interferences and is therefore highly nonlinear, following the squared cosine law of the phase difference. This is a large difficulty that has triggered a lot of research to retrieve the phase amplitude and avoid dead zones when the destructive interferences make the signal vanish. This is a relatively minor issue for acoustic sensing since the small amplitude makes the response linearized and the released requirement of a high spatial resolution enables the implementation of a large redundancy.

When measuring other quantities such as temperature and static deformation, an accurate quantitative value must be retrieved and this requires a specific approach in coherent Rayleigh sensing. Temperature directly and linearly impacts the optical path length through 2 concurring effects: simple material thermal expansion and a change of refractive index with temperature. The optical path length is similarly changed when the fiber is elongated by static deformation. This causes a significant change in the interference pattern on the backscattered intensity time trace and the information apparently looks entirely jammed.

Actually, the phase shift created by these variations results from the product of the light frequency with the optical path change. The effect of this latter change can be compensated by a precise frequency shift to retrieve the original interference pattern. Practically, the sensing optical fiber is successively probed by light pulses with incremental frequency steps and the frequency shift can be precisely determined at each position by correlating the response with that obtained before the change in temperature or strain is applied.

This technique was first implemented using a coherent *frequency-domain reflectometry* to achieve fast and very sharply spatially resolved measurements (down to 1 mm), but over a restricted distance range (some metres) [109]. More recently, a time-domain implementation has been demonstrated and covers a distance range equivalent to those of Brillouin sensors, with the further advantage of an enhanced sensitivity to temperature/strain by some 3 orders of magnitude, totally equivalent to that obtained from FBGs, since ruled by the same physical effect [110]. Paradoxically, it turns out that this extreme sensitivity may be a penalty for many applications, since a milliKelvin resolution is seldom required and it limits the overall temperature range that can be addressed with a simple instrumentation.

In contrast with Brillouin sensing, another drawback is the absence of absolute reference and all measurements are relative by detecting the change from a previous situation. A reference can be only obtained by placing the entire sensing fiber in a controlled environment and then detecting changes with respect to this reference. This requires an instrumentation with a very high stability that is not yet proposed in commercial systems.

It remains that this technique shows a high potential, regarding its large response, its high sensitivity, and the requirement the access to a single fiber end, unlike the most advanced Brillouin sensors based on the stimulated flavor of the interaction.

B. OPPORTUNITIES AND CHALLENGES

Optical fiber sensing will definitely be an omniscient key player in many fields since it gives a proper response to the societal concern for a safer environment protected from human and natural threats. They are now routinely used to detect intrusions, fire in tunnels, leak detection along pipelines, and deformations of large civil engineering structures, as well as early warning of ground slides, snow avalanches, and rock falls. They also enable the optimization of the operation of many energy systems, for instance by monitoring the thermal load along electrical power lines and the deformation of blades in wind turbines. They are already legally required in many major critical installations that can cause a major threat to the population and an ecological disaster.

While Raman and Brillouin sensors have now reached a mature development and no progress is expected more than incremental, distributed coherent Rayleigh sensing has still a margin for further developments and makes it a valuable alternative to Raman and Brillouin sensing. The signal processing remains complex, and there is a large space for improvement using advanced data processing techniques based on the latest developments brought by artificial intelligence and neural networks.

A more disruptive progress would be to devise a system that is actually designed to optimize the sensing response to a designated quantity: currently, the optical fiber sensors are exploiting processes scaled by the native natural response of the material. It would be much more efficient to artificially induce a response that is properly scaled for the application and minimize interfering cross-sensitivities.

An approach has been recently proposed in this direction by inducing a birefringence along the optical fiber through a proper design of the fiber structure. The way the birefringence is created in the optical fiber can make it predominantly sensitive to a given quantity, while reducing the sensitivity to another. This way it has been possible to discriminate the temperature-strain cross-sensitivity [111, 112] and also render an optical fiber sensitive to hydrostatic pressure [113,114].

Another possibility is to take advantage of the newly developed hollow core fibers, in which the light does not essentially propagate in silica glass. These fibers can be filled with fluids that may have an interesting and more dedicated response for sensing. For instance, it has been demonstrated that by filling a hollow core fibers with an ordinary gas at high pressure (such as nitrogen or carbon dioxide), the Brillouin response can be substantially enhanced and the sensor can be made sensitive only to temperature with no strain cross-sensitivity [115].

Finally, a very innovative approach has been recently proposed by exploiting specific interactions involving the entire volume of the optical fiber (not only the central core region) and making it sensitive to the condition of the material closely surrounding the optical fiber. This may be achieved by optically generating transverse acoustic vibrations using the effect designated as *forward Brillouin scattering*: these acoustic vibrations are probing the surrounding material at the fiber boundary and are then reflected on this interface to return the information to the light guided in the fiber core [116,117,118]. This can also be achieved by dynamically coupling the light into the so-called cladding modes that have light propagation properties directly dependent on the surrounding medium. This light is then back-coupled using a similar process to retrieve the information [119].

This field of research leaves a large space for creativity that is significantly stimulated by the interest of end users and the vast impact of these sensors on the life quality and by the societal awareness on the necessity of an optimum use of our limited natural resources.

VI. RECENT PROGRESS OF ELECTROMAGNETIC METASURFACES ENHANCED TERAHERTZ SENSING

A. INTRODUCTION

Paragraph Terahertz (THz, $f = 1$ THz $= 10^{12}$ Hz) waves generally refer to electromagnetic waves within the frequency range of 0.1~10 THz (wavelength λ is 0.03~3 mm), which is located between infrared and microwave. It has many unique advantages compared with electromagnetic waves in other frequency bands owing to its special position in the electromagnetic spectrum, e.g., broadband, low radiation, high transmission, and strong spectral analysis [120–123]. In particular, the terahertz bands contain a large number of characteristic spectra related to the vibration, rotation, and interaction between organic molecules and biomacromolecules. Combined with the characteristics of low energy and low radiation of terahertz waves, the terahertz time-domain spectroscopy (THZ-TDS) has shown tremendous application foreground in the field of biological and chemical sensing [124]. Hence, the THz spectral signals containing important information on the reactive substance type, composition, and quantum interaction process can be obtained by the THz coherent measurement technique. And further, realize the THz sensing detection of substance type determination or quantitative analysis through the terahertz characteristic spectral response [125–127]. However, due to the scarcity of high-power THz sources, the interaction between THz wave and analyte is weak, which greatly hinders the widespread application of THz technology in THz sensing [128].

Recently, with the discovery of electromagnetic metasurfaces, especially composed of metallic microstructures and two-dimensional materials (mainly graphene and MoS2), which support surface plasmon polaritons (SPP) electromagnetic response characteristics similar to optical bands in the terahertz bands [129–131]. The researchers concentrated on developing metasurfaces that support the significant enhancement of THz electric fields, providing a feasible platform for improving the interaction between THz waves and analytes to achieve THz sensing enhancement.

B. GENERATION AND ENHANCED SENSING PRINCIPLES OF THZ METASURFACES

Early studies of SPP focused on visible and ultraviolet wavelengths that match the plasma frequencies of most metals [132]. However, most metals exhibit the physical properties of a perfect conductor (PEC) in the THz bands, and the SPPs electromagnetic wave modes supported by the flat metal interface are very weakly constrained, which is unable to form a localized effect of the electromagnetic field [133]. This limits the research and application of metal SPP in low-frequency bands such as THz to a great extent. In 2004, the theoretical research results of Pendry *et al.* showed that evenly arranged square holes etched on a flat metal surface would generate SPP surface wave modes similar to the visible wavelengths, confining the electromagnetic field in the sub-wavelength space range [133,134]. The surface wave mode generated by metal microstructure is also known as spoof SSPP, whose electromagnetic response is completely dependent on the topography of the metal microstructure, forming a variety of SSPP wave modes at any frequency position by changing the size of the structure.

In 2008, Williams *et al.* successfully extended the research of SSPP to the THz bands based on the square hole structured metal surface [135]. The energy of the THz electromagnetic field on the metasurface modified by the geometric microstructure is concentrated in a narrow space on the surface of the structure, realizing the near-field enhancement effect of the THz electromagnetic field, which can be seen from the propagation simulation of the SSPP. The interaction between THz waves and analytes can be dramatically promoted based on the strong local field caused by the SSPP effect, achieving the detection of trace samples after the introduction of analytes on the metasurface. The reflected or transmitted THz wave properties such as intensity [136], phase [137], and polarization [138], that carry the electromagnetic response information of the sample, will change with the modulation of the metasurface, which can be used to identify analytes. In essence, the surface plasmon resonance (THz-SPR) sensor is the perception of the electromagnetic parameter (refractive index) of the measured analytes in the terahertz bands.

In addition, in 2009, Jablan *et al.* discovered that graphene exhibits metallic properties in the mid-to-far infrared and THz bands and can support SPP that is analogous to metals in the optical bands [130]. Compared with metal metasurfaces, the upper and lower surfaces of graphene support more localized SPP wave modes with effective wavelengths that are 2 to 6 times smaller than the excitation wavelength, and the propagation distance reaches hundreds of microns, thus ensuring stronger interaction sample between samples and THz waves [139,140]. More importantly, dynamic modulation of SPP wave resonance response mode can be achieved by changing the loading voltage of grapheme [129]. These important discoveries guide a new direction for the research on the construction of dynamically tunable THz-SPR sensor devices based on two-dimensional materials.

C. DEVELOPMENT AND APPLICATION OF THZ-SPR SENSOR

The emergence of terahertz metasurfaces has introduced new ideas for applications of THz-TDS technologies in chemical and biological spectral analysis and greatly expanded the scope of these applications. Therefore, a worldwide upsurge of research interest in THz metasurfaces sensing enhancement was started [141]. Specifically, the THz-SPR metasurface sensors composed of metallic microstructures and two-dimensional (2D) materials (mainly graphene or MoS_2) are the most popular two types.

1) THZ-SPR SENSOR BASED ON METAL METASURFACE. Metal metasurfaces can be further subdivided into propagating metasurfaces (PSPS) and localized metasurface (LSPS). In the research of THz-SPR sensor based on PSPS, FMiyamaru *et al.* first applied THz-SPR in sensing detection in 2006 [142]; Subsequently, Tian *et al.* used THz spectrum enhanced by metal hole array PSPS to realize sensing identification of methanol ($^{12}CH_3OH$) and its H/D exchangeable isotope ($^{12}CH_3OD$) [143]; He *et al.* realized the distinguishing between different glutamic acid isomers in powder form [144] and types of gasolines [145] based on hole structural PSPS; Hasebe *et al.* took advantage of THz-SPR sensor with square hole to achieve quantitative analysis of the interaction degree between lectin and glucose molecules [146]; Ng *et al.* enhanced the absorption of trace lactose samples through blade scattering coupling to generate SSPP surface wave upon metal groove PSPS, forming obvious "spectral fingerprints" [147]; Based on the same enhanced absorption sensing mechanism, Lee *et al.* utilized nanoslot-array PSPS to realize highly sensitive and selective detection of steroid hormones [148]; Besides, this research group also used similar rectangular slot PSPS to build a label-free THz biosensor, and applied it in the sensing detection of three AI viruses (H1N1, H5N2, H9N2) [149]. Meanwhile, another kind of LSPS composed of evenly arrayed metal geometric microcells, can support a variety of singular electromagnetic or SSPP resonant modes with ultrahigh Q value, as long as its structural units are reasonably designed. It equally plays an important role in the design and application research of THz SPR sensors. Singh *et al.*, for instance, successfully utilized an asymmetric double split-ring array LSPS to stimulate low-loss quadrupole and Fano resonance with very high Q, and used it for THz-enhanced sensing [150].

2) DYNAMIC ADJUSTABLE THZ-SPR SENSOR BASED ON TWO-DIMENSIONAL MATERIALS. Compared with the SSPP manipulated in metal microstructured metasurfaces, a more confined SPP wave mode can be supported in the upper and lower surfaces of 2D materials, whose resonant properties can be adjusted flexibly. Hence, 2D materials become a new research direction for exploring highly sensitive and dynamically tunable THz-SPR sensors [151,152]. A variety of novel hybrid sensing constructures with graphene have emerged successively. For example, Gao *et al.* proposed a graphene/buffer layer/silicon grating structure [153]. Originated from the grating guided mode resonance excitation, it can work in the infrared frequency band dynamically. Then, Zhao *et al.* used this graphene composite structure in the highly sensitive refractive index sensing [154]; Utilizing ribbon-patterned graphene, Islam *et al.* proposed a tunable localized SP metasurface THz-SPR sensor with a maximum sensitivity of 66 THz/RIU [155]; Tang *et al.* designed a THz refractive index sensor composed of graphene-Bragg reflector multilayered structure, whose maximum sensing sensitivity reached 407.36 deg/RIU [156]; Ge *et al.* proposed a graphene metasurface sensor consisting of two ribbons and rings, and obtained a sensing sensitivity of 1.08THz /RIU [157].

D. DISCUSSION ON FUTURE DIRECTIONS

The traditional means of obtaining THz characteristic spectral information of substances mainly adopt transmission and reflection THz-TDS detection systems. However, THz pulses need to be directly irradiated on the sample regardless of the detection method adopted. Restricted by the requirements of the sample size, it is difficult to realize the sensing and detection of trace samples by using the direct irradiation detection method. The primary cause is that the relatively small extinction coefficient of most substances in the terahertz bands hinders to exhibit absorption characteristics, and the terahertz wavelength spans a wide range, which requires a thicker sample (usually on the order of millimeters) to ensure the interaction between the THz waves and the substance, and then obtain effective THz spectral information that can reflect the composition of the sample substance. Therefore, the research of proteins, DNA, RNA, and other biomacromolecules using THz-TDS technology requires high experimental costs because these trace molecules need to be isolated from a large number of organisms. Therefore, how to improve the sensitivity of terahertz sensing technology and realize the effective detection of trace analytes has become a major problem that needs to be solved urgently in the promotion of THz-TDS technology in the fields of chemical and biological sensing.

Metal microstructured metasurfaces can change the spatial distribution of electric fields in the transmission process of THz wave, thus realizing the field enhancement. Unique SSPP responses in an arbitrary THz band can be generated by appropriately tailoring the size of surface geometry constructions. Furthermore, the metal metasurfaces are subdivided into two categories: one is the metasurface formed by etching periodic geometric unit arrays on flat metal surfaces; the other is compounded from uniform arrangement of metal geometric microstructure units (mainly split-ring resonator (SRR)), also known as metamaterials. Depending on the supporting SSPP propagation characteristics, the former is essentially a propagating spoof plasmon surface (PSPS) that allows SSPP propagates along the metal surface; The latter can be regarded as a localized spoof plasmon surface (LSPS), whose SSPP supported can only be tightly confined in the metal micro-units and cannot propagate. These two categories of SPR controlled by metasurfaces are typical representatives of the THz-enhanced sensing technology. Because of the high sensitivity displayed, they have been successfully used in qualitative or quantitative sensing detection of various biochemical samples. From the above research status at home and abroad, it can be seen that the use of metal microstructured metasurfaces to form various unique electromagnetic resonance enhancement effects has achieved many gratifying results in the application research of enhanced terahertz sensing. Nevertheless, current research still faces significant challenges to be aware of, which should be solved in the future. Below are some topics that the authors believe are possible future lines of research.

1) ELIMINATION OF SUBSTRATE EFFECT. By the resonance spectrum translation and resonance spectrum intensity changes based on THz-SPR sensors with different resonance responses, different kinds of trace samples can be qualitatively analyzed or perform quantitative analysis on trace samples of the same type but with different control variables. Besides, it can also be used to determine the type and concentration of trace liquid. However, the electric field enhancement of most metal microstructured metasurfaces is mainly concentrated near the metal cusps or split rings, and due to the existence of metasurface substrate, only the enhanced THz electric field in part of the region can be used to enhance the interaction with the substance, so it is difficult to make full use of the enhanced THz electric field. As result, the sensitivity of the THZ-SPR sensor is limited. From this, Park *et al.* proposed to greatly improve the sensitivity of THz-SPR sensor by introducing etching grooves into the capacitor-inductance gap areas of LC resonance produced by SRRs [158]. However, it is difficult to make full use of the excited electric field directly below the metal microstructure substrate, and the influence of the substrate effect cannot be completely eliminated, no matter using low refractive index substrate or ultra-thin substrate, or through substrate etching. How to maximize the local electric field generated by metal metasurface to ensure strong interaction and further improve the sensitivity of the sensor will be one of the key research contents of THz-SPR sensor in the future.

2) TWO-DIMENSIONAL MATERIALS. Secondly, it is also one of the future development trends to construct ultra-high-sensitivity THz-SPR sensors using unique dynamically adjustable high-localized SPP wave modes supported by two-dimensional materials such as graphene. Recently, another 2D material, molybdenum disulfide (MoS_2), has received similar attention due to its unique photoelectric and physical characteristics. MoS_2 can also support SP in the THz domain and has higher modulation efficiency, field constraint coefficient, and bandgap structure than graphene. So, it's expected to replace other semiconductor materials in the application of THz sensing devices [159–162]. Benefiting from the flexibly tunable properties and the sensibility to change with external factors including light, electricity, and temperature, predictably, MoS_2 has great application potential in THz-enhanced sensing field alike [163]. However, the fabrication of two-dimensional material-reinforced structures is usually accompanied by an increase in structure volume and complexity, which is not conducive to the processing of devices, and poses a challenge to the processing of THz-SPR sensors.

3) LSPS INTEGRATED MICROFLUIDIC. At present, the most common metallic metasurfaces are excited by SSPPs directly irradiated by THz waves. Due to the strong damping effect of polar liquids, the THz amplitude spectrum formed by resonance is severely broadened. Therefore, traditional methods based on THz amplitude sensing readout methods are difficult to effectively sense and characterize small changes in aqueous and other polar liquid buffer sensing media based on frequency shifts and intensity changes in the spectrum. Therefore, considering the practical application requirements of liquid trace detection, the construction of integrated THz-SPR sensors combining microchannels with LSPS has gradually shown great application potential in the detection of polar liquids and other high-loss media. Hu *et al.* replaced the medium layer in a cross-unit absorber with a microchannel to obtain higher sensing sensitivity. The interactions are facilitated by increasing the spatial overlap between the sample and THz field on the LSPS surface [164]; Huang *et al.* designed a prism coupling metal groove THz-SPR sensor, which combines PSPS with attenuated total reflection (ATR) to enormously alleviate the severe absorption of THz waves from polar liquid and realizes the highly sensitive sensing detection of polar liquid [165]. This also makes it another important development direction of terahertz sensing in the future, which is of great significance for promoting the popularization and application of THz-SPR sensing devices.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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